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Journal of Sedimentary Petrology

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Journal of Sedimentary Petrology

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THE PETROGRAPHIC CHARACTERS OF SOME EOCENE SANDS FROM SOUTHWEST TEXAS

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This paper describes the petrographic characters of a number of Eocene sands collected in Atascosa and Frio counties in southwest Texas. In this region the Eocene formations, sands, clays, greensands, and quartzites, and minor amounts of limestone, outcrop in belts roughly parallel to the coast. The dip is coastward and is generally about one degree. A table of the Eocene formations of the region is given below:

Yeager clay	Non-volcanic calcareous clay.
Fayette sandstone	White, gray, greenish and buff sandstone, lenses of varicolored limy shale and clay, volcanic ash.
Yegua formation	Selenitic and carbonaceous dark gray clays, thin beds and lenses of sandstone and sand.
Cook Mountain formation	Varicolored sandstones, greensands, gray clay, lenses of limestone.
Mount Selman formation	Varicolored clays and sandstones, lignite and limestone lenses.
Bigford formation	Chiefly varicolored clay with some sandstone and lignite.
Carrizo sandstone	Chiefly coarse sandstone with minor amounts of clay.
Indio formation	Mostly thin bedded sands and shales with considerable lignite.

The Midway, Cook Mountain, and Fayette are fossiliferous, certain other formations are only sparingly fossiliferous, and some like the Carrizo have yielded only plant fossils. The recognition of the formations in the field is sometimes made only with difficulty and the classification of the series is perhaps open to revision. Identification of well samples frequently presents even greater difficulties, than the correlation of surface materials, especially with

samples which do not contain fossils. As shown in the table, the formations are somewhat similar lithologically and the conditions of sedimentation involved must have been fairly constant. The object of the present study was to ascertain the value, for correlation purposes, of the petrographic characters of the sands of the various formations. The investigation was limited to a study of samples from a restricted area and is to be regarded as a preliminary and not a final study. It was considered that a study of a limited number of specimens would show whether an extended similar study of the Eocene of the whole southwest Texas area would be of value.

LABORATORY PROCEDURE

The specimens studied were outcrop samples of sands from the Indio, Carrizo, Mount Selman, Cook Mountain, Yegua, and Fayette formations. These were selected to show the range of texture and lithology present in the sands of each formation. Each sample was subjected to an examination for texture, shapes of grains, and mineral composition. The procedure was much the same as that reported in many recent papers and will be only briefly mentioned.

The texture was obtained by sieving the samples. The sieves employed had openings of 2, 1, 0.589, 0.295, 0.147, 0.074 millimeters. Separations gave seven grade sizes well suited to the sands under investigation. The amount of each grade size of a given sample was calculated as percentage weight of the total sample and plotted on the graphs shown in Figure 1.

The shapes of the sand grains were obtained by a study of photomicrographs of the grains. Two representative fields from each sample containing a total of at least 200 grains were photographed and each grain classified as round, subround, subangular, or angular. These terms were used with the significance given them by Graham[1] in his recent paper on the Cambrian sandstones of Minnesota. The percentage of the total for each shape was computed and plotted in the graphs shown in Figure 2.

The minerals of the sands were separated into light and heavy groups by the use of bromoform, and studied with the binocular and petrographic microscopes. It was soon found that the light minerals were very similar in all samples so that no quantitative study was made of them. The study of the heavy minerals was partly

[1] Graham, William A. P., A Textural and Petrographic Study of the Cambrian Sandstones of Minnesota: Jour. Geol., XXXVIII, 696–716 (1930).

quantitative in that estimates were made of the relative amounts, in the heavy concentrate, of each mineral found. The quantitative expressions used are rare (1 to 10 percent), common (10 to 20 percent), abundant (20 to 50 percent), and very abundant (more than 50 percent of the concentrate). These estimates were obtained by counting 100 or more grains in microscope fields. While these expressions give a rough estimate of amounts they fail to show the noteworthy difference between a mineral present in one or two grains, and one of which as many as ten grains have been identified. The relative amount of the total heavy concentrate was expressed by use of the terms large, medium, and small. The largest heavy concentrate found did not exceed 0.50 percent so that more exact terms could not be used.

TEXTURE

The results of the study of the textures of the sands are shown in Figure 1. Each graph represents a sample of sand and the graphs of each formation are arranged from top to bottom in order of decreasing coarseness. The difference in outline of the different graphs shows general textural differences. The quantitative expression of these differences is found in the percentage amounts of the several grain sizes shown.

Samples of the Carrizo sands differ most widely and probably characteristically from the others. Although the Carrizo samples were selected to show the finest as well as the coarsest facies, no sample failed to contain at least a fraction of a percent of grains larger than 2 mm. and usually a slightly larger amount of grains between 1 and 2 mm. in size. All of the Carrizo sands show this characteristic and all show a rather general distribution of grains through all seven size grades.

Samples of sands from the other formations do not show such distinctive textural differences and any differences present are of smaller diagnostic value. The Indio and Yegua sands show a grouping into the three finest grades, no grains larger than 0.295mm. being found. This is in contrast to the other samples which contain variable amounts of grains in coarser grades. The Cook Mountain and Fayette sands are quite similar in texture showing with one exception, a distribution through the five lower or finer grades. The Mount Selman sands are intermediate in textures between the Indio-Yegua and Cook Mountain-Fayette sands. The samples of the Mount Selman examined did not contain grains larger than

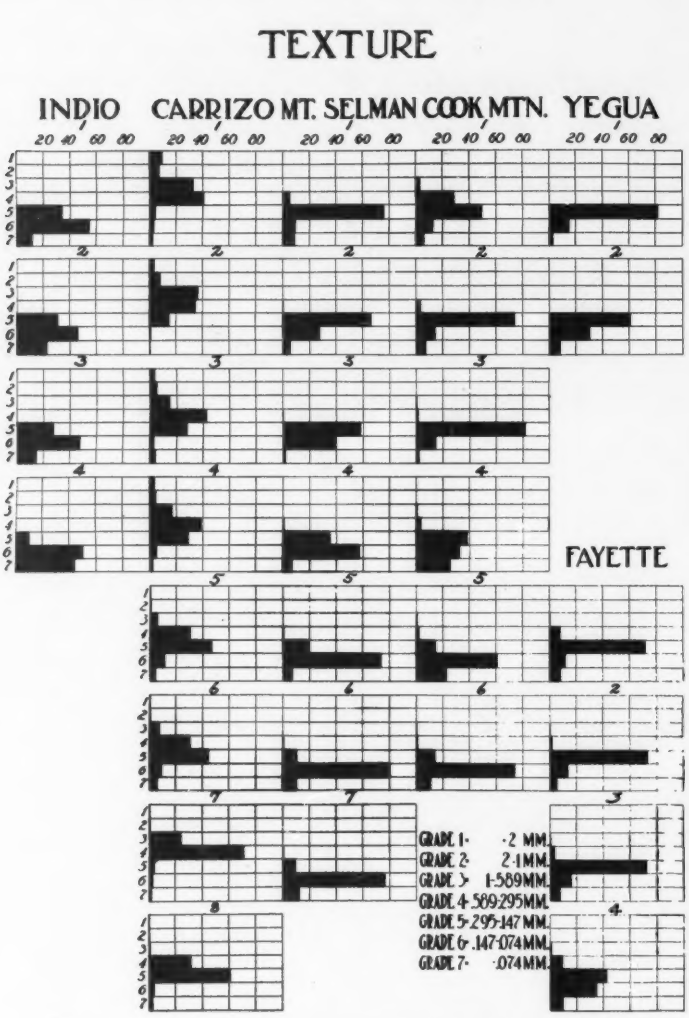

Figure 1. Graphs showing the texture of sand grains in sands from the Eocene formations.

Figure 2. Graphs showing the shape of samples of sands from the Eocene formations.

0.589 mm. Since seven samples were tested this difference may be characteristic of the formation.

SHAPES OF GRAINS

Figure 2 shows the results obtained from the study of the shapes of the sand grains. The sands of the various formations show a general similarity in this respect and show also a relatively small amount of rounded grains, somewhat larger amounts of subrounded grains, a maximum amount of subangular grains, and generally a rather small amount of angular grains. The rounded

grains of glauconite in the Cook Mountain sands were excluded from this study so that the graphs show detrital grains only.

The largest number of rounded grains found in any sample was found in Cook Mountain No. 1, and Carrizo No. 4 contains a number nearly as large. All Fayette samples contained appreciable amounts of rounded grains, a condition not found in samples from the other formations. The differences present are not believed to be important from the diagnostic standpoint. The study, however, does give information on the erosional history which these sands have undergone and suggest a similar history.

MINERAL COMPOSITION

Light Minerals. The light minerals with minor exceptions were found to be much the same in all samples examined. Quartz, microcline, plagioclase, and glauconite were identified. Most of the quartz was phanerocrystalline but cryptocrystalline varieties were present in all samples. Some of the quartz showed optical strain and some of it did not exhibit this character. Inclusions were common in the phanerocrystalline type but did not differ in samples from different formations.

All samples contained plagioclase and samples from each formation contained microcline. The feldspars were relatively fresh and unclouded from alteration. The amount of feldspar was greater in samples from the Carrizo and Fayette though the amount was small in comparison with the total of the sample, averaging, perhaps, 5 percent. Glauconite was found in rather large amounts in most of the Cook Mountain samples but was absent from others. The mineral was also found in very small amounts in one Yegua sample. The mineral is known to occur in the Mount Selman but samples of Mount Selman glauconitic sandstone were not included in this study.

Heavy Minerals. The heavy minerals found in samples from the various formations are shown in the accompanying chart. As explained previously an attempt was made to express the results of this study quantitatively because it was expected that any great differences in minerals of the sands would be found among the heavy minerals. The chart shows that a few minerals, leucoxene, ilmenite, magnetite, tourmaline, and zircon constitute the bulk of the heavy minerals but that several other minerals are present, though, in smaller amounts than indicated by the expression used on the chart.

HEAVY MINERALS

Formation and Sample	Amount	L	I	Mt	T	Z	C	S	R	M	B	G	Ti	A	Sp	Br	Be
Indio																	
1	Med.	A	A	C	R	C	R	R	R	R		R		R			
2	Small	A	A		C	C	R		R	R							
3	Small	A	C	C	R	A	R	R	R		R						
4	Med.	A	A	C	R	C		R	R	R		R					
Carrizo																	
1	Small	A	A	R	R	C		R	R	R							
2	Small	A	A	R	R	R	R	R	R	R	R						
3	Med.	A	C	R	R	A	R	R	R								
4	Med.	A	C	R	R	A	R	R	R	R							
5	Med.	A	C	C	R	A	R	R	R	R							
6	Med.	A	C	R	R	A	R	R	R	R			R		R		
7	Large	A	A	A	C	C	C				R						
8	Small	A	C	R	R	C	R	R	R	R							
Mount Selman																	
1	Med.	A	A	R	R	C	R	R	R	R	R	R		R			
2	Large	A	A	R	R	C	R	R	R	R	R	R		R		R	
3	Med.	A	A	R	C	A	R	R	R	R							
4	Large	A	A	R	R	C	R	R	R	R	R	R					
5	Small	A	A	R	R	A	R	R	R	C				R			
6	Med.	A	A	R	R	C	R	R	R	C	R						
7	Large	A	A	R	R	C	R	R	R	R	R						
Cook Mountain																	
1	Small	A	A	R	R	R	R	R	R	R							
2	Small	A	A	R	R	C	R	R	R	R							
3	Small	A	A	R	C	R	R	R	R	R							
4	Large	A	A	C	R	C	R	R	R	R	R						
5	Large	A	A	R	R	C	R	R	R	R	R						R
6	Small	A	A	R	R	C	R	R	R	R							R
Yegua																	
1	Med.	A	C	R	R	C	R	R	R	R							
2	Small	A	A	R	R	C	R	R	R	R							
Fayette																	
1	Small	A	C		R	C	R		R			R	R				
2	Small	A	C	R	R	C	R						R				
3	Small	A	C	R	R	A	R	R	R			R	R				
4	Med.	A	C	R	R	A	R		R			R	R				

L—Leucoxene, I—Ilmenite, Mt—Magnetite, T—Tourmaline, Z—Zircon, C—Cyanite, S—Staurolite, R—Rutile, M—Muscovite, B—Biotite, G—Garnet, Ti—Titanite, A—Anatase, Sp—Spinel, Br—Brookite, Be—Benitoite.

A—Abundant, 20–50%, C—Common, 10–20%, R—Rare, 1–10% of the Bromoform concentrate.

Under leucoxene, the most abundant mineral as listed, is included opaque brownish to grayish material much of which shows all stages of alteration from ilmenite. Such grains gave a chemical test for titanium but some of the material listed as leucoxene may include other minerals since not every grain was tested chemically or optically. Other minerals that might be included are clouded zircon and rutile.

Grains listed as zircon include transparent, colorless to grayish euhedral crystals showing no rounding, and rounded wine colored crystals. It is possible that the latter are *xenotime* (YPO_4) a mineral very similar to zircon optically, but considerably softer. Such grains were observed in all samples for which zircon is shown and do not constitute a diagnostic character of any formation.

A mineral identified as *benitoite* ($BaTiSi_3O_9$) was found in Cook Mountain samples Nos. 5 and 6. The mineral resembles blue tourmaline in general appearance but is optically positive, has higher indices of refraction, and exhibits a variation in color in a single grain. Only two grains of the mineral were found and a complete determination of all of the optical constants could not be made.

One grain of green spinel was found in Carrizo No. 6, one brookite in Mount Selman No. 2 and a few grains of anatase in samples from the Indio and Mount Selman. Other minerals in larger amounts but restricted distribution include garnet, titanite and micas.

The results obtained from the study of the heavy minerals yield little of diagnostic value for recognition of samples of the several formations. A number of minerals such as, benitoite, spinel, brookite, and anatase restricted to one or two formations are present in very small amounts and not in all samples of a given formation. Minerals abundant in one formation are generally abundant in the others. A few assemblages may be characteristic and of value for purposes of correlation. Among these is a relatively large amount of titanite and the absence of micas in the Fayette, fairly large (estimated 8 percent) amounts of garnet in some Indio samples, and relatively large amounts of biotite in samples from the Mount Selman. The total amount of samples used to secure the heavy concentrate was relatively small and it may be that the use of larger samples would emphasize the differences mentioned and perhaps show others.

The minerals, both light and heavy, of the whole suite of sam-

ples are more characteristic of metamorphic parent rocks than of any other type. Relatively large amounts and the constant presence of cyanite and staurolite are significant. Furthermore, some of the minerals present are fairly unstable suggesting that the sediments of these Eocene sands have not passed through a long sedimentary history.

SUMMARY AND CONCLUSIONS

The results of this study may be summarized as follows:

1. The texture of the Carrizo sand differs so markedly from that of other Eocene sands that it has value for correlation purposes.

2. Minor textural differences exist, between the other sands, but have questionable value for correlation purposes.

3. The grain shapes of the sands are generally similar. All sands show a preponderance of subangular grains and a minimum of rounded grains.

4. Minor mineralogical differences exist between the sands. These are probably of some value for correlation purposes but will not serve as the principal basis for correlation of samples from the various formations.

5. The mineral assemblage suggests parent metamorphic rocks and a relatively short sedimentary history.

6. Since the investigation of a relatively few samples from a restricted area yielded a few results of value, its extension might yield results of greater value.

A PETROGRAPHIC STUDY OF THE CHESTER SANDSTONES OF INDIANA

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ABSTRACT

Study of the mineralogy of the Chester sandstones of southwestern Indiana shows an abundance of a very few minerals, and a trace of many more. The heavy minerals consist of 50 to 100 percent leucoxene, 25 to 50 percent zircon, and 10 to 25 percent tourmaline. Rutile, ilmenite and brookite compose from 1 to 10 percent of the heavy minerals. Magnetite, anatase, garnet, hornblende, kyanite, muscovite, hypersthene, pyrite, chlorite and barite are present sporadically and always in small quantity. The light minerals consist of quartz, feldspar, and calcite.

The outstanding feature of the mineralogy of the Chester sandstones is the occurence and nature of the mineral leucoxene together with the other closely associated titanium-bearing minerals, brookite and rutile. It is recognized that the titanium oxide minerals, brookite and rutile, are developed authigenically from the decomposition of leucoxene.

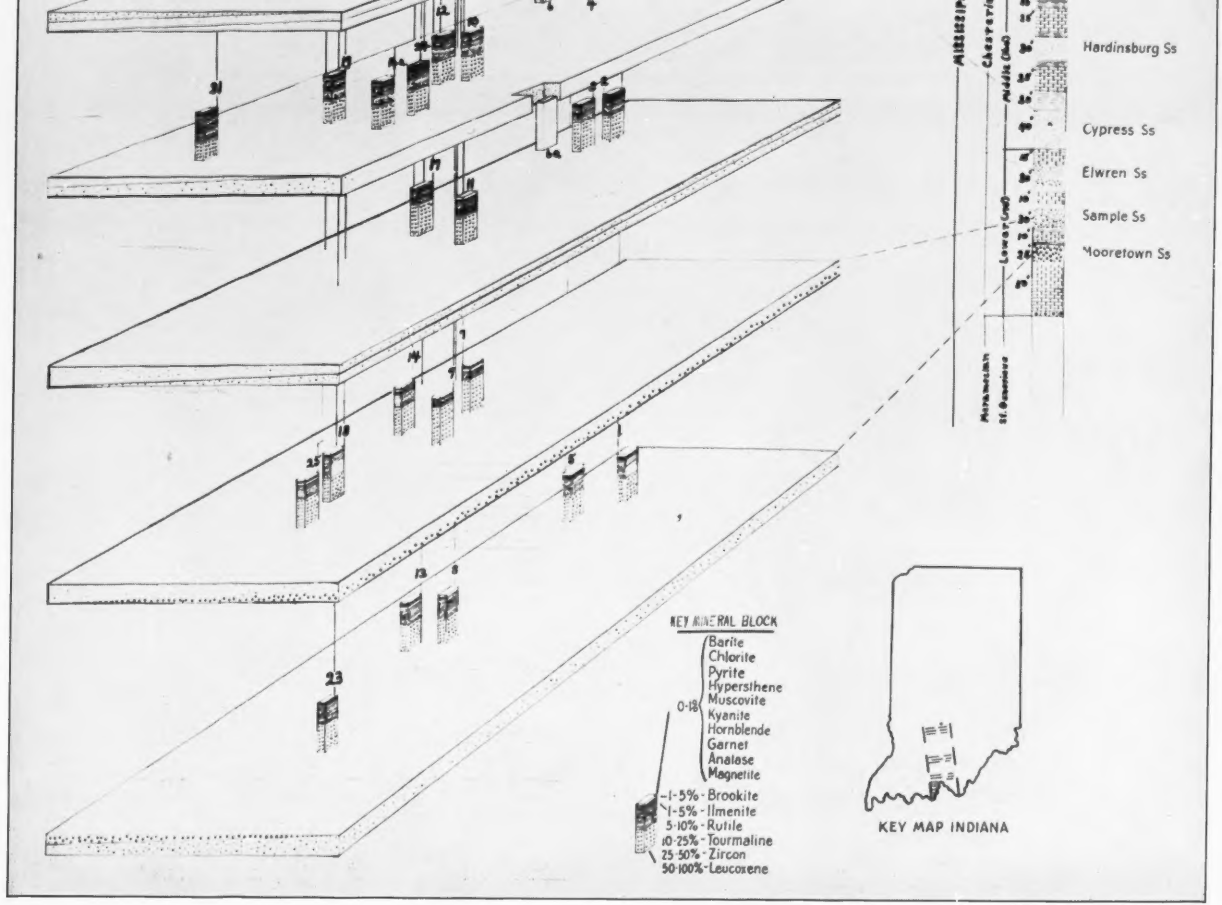
INTRODUCTION[1]

It is the purpose of this paper to give the results of studies of the sandstone members of the Chester series of southern Indiana and an application of these results to correlation and to determining the sources of the sediments. The study consists in large part of a petrographic examination of the heavy minerals in the sands. The light minerals were cursorily examined, especially in view of aid they might give in interpreting the history of the sediments. The sedimentary materials were collected from the southwestern part of Indiana, as shown on key map in accompanying block diagram (Plate 4). Detailed descriptions of the stratigraphic relations of the Chester series are given by Malott[2] and Cumings.[3]

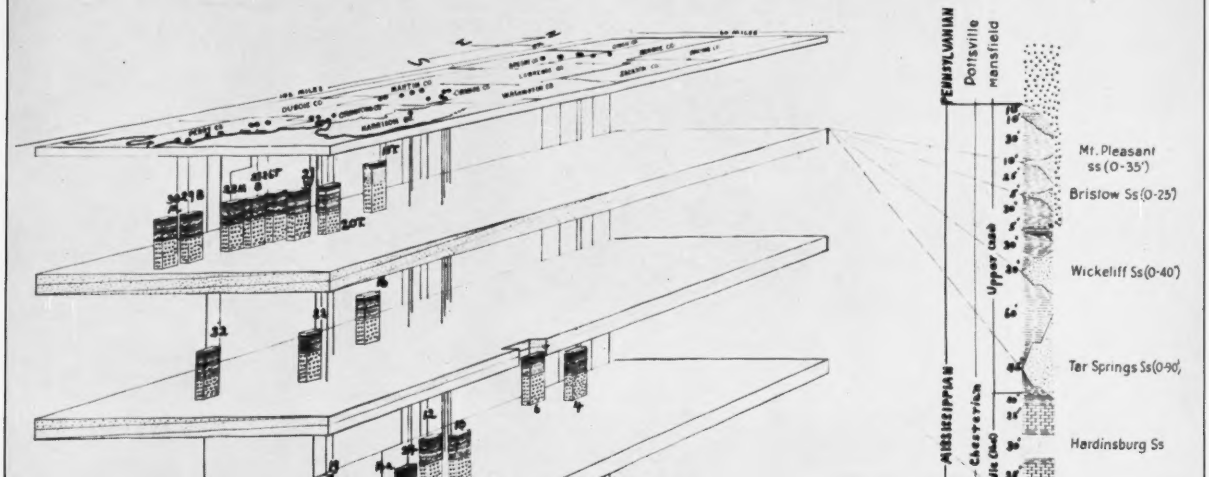
[1] The writer wishes to thank Dr. W. H. Twenhofel and Dr. R. R. Shrock, of the Department of Geology of the University of Wisconsin, under whom this research was done, for many helpful suggestions in carrying on the work. The writer is also indebted to Dr. A. N. Winchell and Dr. R. C. Emmons of the same department. Particular thanks are due to Dr. C. A. Malott of the Department of Geology of the University of Indiana, whose kindly cooperation with the writer in field study and sampling of the formations made the work possible.

[2] Malott, C. A., The Upper Chester of Indiana, Proc. Ind. Acad. Sci., XXXIV, 103–132 (1924); the "American Bottoms" Region of Eastern Greene County Indiana, Ind. Univ. Studies, No. 40 (1919).

[3] Cumings, E. R., Handbook of Indiana Geology, Part IV, 515–518 (1922).


Hardinsburg Ss
Cypress Ss
Elwren Ss
Sample Ss
Mooretown Ss
KEY MINERAL BLOCK
0-18
Barite
Chlorite
Pyrite
Hypersthene
Muscovite
Kyanite
Hornblende
Garnet
Anatase
Magnetite
~1-5% - Brookite
~1-5% - Ilmenite
5-10% - Rutile
10-25% - Tourmaline
25-50% - Zircon
50-100% - Leucoxene
KEY MAP INDIANA

DIAGRAMMATIC REPRESENTATION OF HEAVY MINERAL DISTRIBUTION IN CHESTER SANDSTONE HORIZONS



DATA ON MINERAL ASSEMBLAGES

Method of Recording Data. In order to make direct comparisons between the kind and amount of mineral present in one formation with that in another, or in another part of the same formation, a block diagram type of graphical expression is included.

The block diagram is made up of a series of segments in which each individual block represents a sandstone horizon of the Chester group. The geological column on the right in the diagram is one constructed by C. A. Malott, in which all the formations making up the Chester series are shown in their true position and with the thicknesses drawn to scale. Only the sandstone members of the Chester were studied and so they are the only members to which names are given in the column and represented in the block diagram. A straight line is drawn from each sandstone member of the column to its corresponding position in the diagram. In the lower and middle Chester a number of sample sections are available and to make the results clear one segment of the diagram represents one sandstone unit. In the Upper Chester, however, outcrops are scarce and thus sample sections are limited, so that the entire Upper Chester is represented by one segment of the diagram.

On the uppermost segment of the diagram a county map is drawn of the part of Indiana from which the samples were taken. The location of the sections sampled is shown by a dot on the map. From the located point a vertical line is drawn down to the particular formation sampled. Where this vertical line intersects the plane of the particular formation sampled, a mineral block is constructed.

The purpose of the mineral blocks is to show graphically the kind and amount of each mineral present in each section. A mineral block represents a composite analysis of all the samples in any one sample section. The mineral blocks are all the same size and are divided into a number of parts in such a way that each part represents by its size the amount (in percentage) of each mineral present. For each mineral there is a definite symbol used in the mineral block. A key block is shown at the bottom of the diagram. The very rare mineral occurrences are grouped in the uppermost part of the mineral bocks. In one instance, that is section number 6a, heavy minerals are absent.

The block system is very diagrammatic but with a true picture of the geological column to the right the diagrammatic character of

the block should not lead to inaccurate interpretation. The usefulness of the block diagram lies in the fact that at a glance a summation of the following essential points of interest is given.

1. The location of each sample section.
2. The horizontal distance between points at which sections are made and the number of times each formation is sectioned.
3. The heavy minerals present in each section.
4. The relative amount of each mineral present.

A study of the mineral blocks illustrates the very striking similarity both in kind and amount of the minerals present in each section. The similarity continues not only throughout each individual formation but through all the formations from bottom to top of the Chester series. This great similarity in heavy mineral content renders it absolutely impossible to recognize any particular formation by its heavy residual minerals.

Leucoxene and its Authigenic Derivatives. The most striking single feature of the mineralogy of the sediments, as illustrated by the mineral blocks, is the abundance of a mineral identified as leucoxene. At least 50 percent and sometimes as high as 75 percent of the heavy mineral crop is made up of white to gray opaque grains. The heavy minerals make up a little less than one percent. The surfaces of these grains range from polished smooth to quite rough. The smooth grains are well rounded and the rough grains are usually irregular in shape. The smooth, round grains appear to be detritals since they were evidently worn smooth through abrasion.

The opaque grains are identified as leucoxene, a mineral for which little precise information is available. The leucoxene particles, by alteration, yield the oxide minerals of titanium, i.e., brookite, rutile, and anatase. The identification as leucoxene is supported by the fact that in a few instances derivation of the opaque grains is seen to be taking place by alteration of the mineral ilmenite. Transitions occur from black metallic ilmenite to particles half black and half white and to entirely white. Examples of ilmenite altering to leucoxene are not common. The process seems to have been in large part carried on prior to final deposition of the sediments for many of the leucoxene grains are spheroidal and polished. Ilmenite is also recognized in the heavy mineral suites as irregularly shaped fragments with no alteration to white

material having taken place. Study of the leucoxene was attempted by means of x-ray analysis but no x-ray pattern was found. The absence of pattern suggests material of an amorphous nature; but as only a small sample of pure material was obtained, the absence of a pattern may be due to insufficient quantity.

Examination in reflected light with medium power objective shows many of the gray opaque grains of leucoxene to bear clusters of tiny yellow crystals of brookite protruding in every direction. The tetragonal brookite crystals have sharp corners and edges and exhibit no evidence of a detrital history. As the matrix of opaque material from which the crystals protrude is quite soft and loosely aggregated, it is considered impossible for the combination of perfect crystals and soft friable matrix to have been incorporated in the sediments as detrital grains and the evidence seems to prove development in the sediments after deposition.

In a few instances grains of leucoxene are found in which the entire surface is indented with many closely spaced rectangular shaped depressions. The depressions are casts of brookite crystals, the brookite crystals probably having been broken away from the leucoxene by mechanical abrasion in treatment of the samples.

Different grains of leucoxene show practically all stages of development of brookite. In every field of view examined there were seen leucoxene grains barren of brookite crystals and others bearing one to a dozen or more perfect crystals. Some grains are made up of a few relatively large brookite crystals radiating from an opaque matrix; the matrix in such instances making but a very small part of the total aggregation. The opaque material in this type of grain is a thin coating of white material plus a concentration of iron oxide on the inside ends of the radiating brookite crystals.

In a sample from the Tar Springs sandstone a large opaque rounded grain was observed in which alteration from ilmenite to leucoxene to brookite was observed. The central part of the grain is composed of black ilmenite; this is flanked on either side by white leucoxene, and protruding from the surface of the leucoxene are a number of brookite crystals.

A second equally important derivation product of the leucoxene is rutile. The transition from leucoxene to rutile may be completely traced, an entire grain of leucoxene changing to crystalline rutile rather than as individual crystals protruding therefrom.

The first step in the alteration is a change from massive opaque

leucoxene to a finely crystalline mass made up of an aggregation of tiny needle-like crystals all oriented in one direction and developed with the side of one crystal in contact with the next. In many instances this produces a finely fibrous or finely striated character in the grain.

In the early stages of development the rutile crystals so developed are a straw-yellow color. Sometimes it is possible to note a change in color from yellow in the central part of the grain to a reddish color on the edges. The massive large crystals of rutile which are fairly common through the sediments are usually deep red in color. Sometimes it is possible to observe in the amorphous leucoxene, which is just beginning to become crystalline, the cleavages typical of rutile. In such cases it is possible to see the beginning of development of a crystalline character taking place between the cleavages. A number of grains which appear on the surface to be detrital grains of rutile were found on close inspection to have either a narrow band through the center or a patch on the side of gray leucoxene. When these same grains are subjected to very light pressure by a fine needle point the whole grain breaks into a great many tiny fragments and the central core is revealed as a very soft and loose aggregation of white opaque material. The rutile is like a shell around a core of opaque material. The tiny broken fragments appear yellow with slight tendency to grade into red on the outside edge. Before fracture many of the leucoxene-bearing rutiles appear deep red. The yellow color appears to be an earlier stage of rutile development and the deep foxy red colored rutiles are considered to be grains which are thoroughly changed over from leucoxene and have already passed through the yellow colored stage.

Further evidence supporting a derivation *in situ* of the rutile, is the presence in the sands of many very large red colored knee-shaped twin crystals of rutile. It seems impossible that such knee twin crystals could have been preserved in an environment of grain erosion such as that to which the containing sands must have been subjected.

The mineral anatase is not discussed since it was not found directly attached to leucoxene grains, but the suggestion is made that it too may have been derived *in situ* from leucoxene. The distinct square shapes of the anatase crystals is evidence that the grains are not of detrital origin.

There remains the problem of determining, if possible, the en-

vironmental conditions under which the brookite and rutile so abundantly found in the Chester formations were produced. The katamorphism of leucoxene to give brookite and rutile derivatives is a process that may have been going on since the time of deposition of the sediments and it may be continuing even today. The occurrence of the oxide minerals in many stages of development is suggestive that the process is a continuous one.

The containing sandstone formations are slightly inclined, are porous and are interbedded between shale and limestone formations. There is opportunity for surface waters to gain access to each of the formations, since they all outcrop on the surface. The opportunity for circulation of ground waters is excellent, since each sandstone unit is similar to a channel with impervious shale layers both above and below.

From the evidence presented it would appear that the principal agent promoting development of the titanium oxide minerals was surface water. It is suggested that circulating carbonated surface waters removed lime from leucoxene and with this breakdown of the leucoxene molecule, TiO_2 separated as brookite or rutile and the SiO_2 became colloidal silica or crystallized as quartz. The causes leading to the crystallization of the TiO_2 in some instances as brookite and in others as rutile are not known. It does not seem probable that either temperature or pressure could have been determining factors. The minerals were undoubtedly formed in a cold water environment. The only possible pressures are those arising from the weight of overlying sediments and according to Malott the Chester series at no time was more deeply buried than 2,500 feet. The porous nature of the sands would permit freedom in the growth of crystals under such conditions.

Laboratory experiment has shown that the two minerals form at high temperatures and "that rutile, the most stable form of titanium oxide, is formed at the highest temperatures, brookite at temperatures considerably lower, and anatase at a point still lower in the scale.[4] High temperature can not be appealed to for explanation of the Chester minerals.

In the anamorphism of clays, Leith and Mead note the development of secondary rutile by katamorphism of biotite, and sometimes amphibole and olivine. The large quantity of rutile in

[4] Clarke, F. W., Data of Geochemistry, U. S. Geol. Survey, Bull., 770, 355 (1924).

shales is attributed by them to recrystallization of titanium compounds during cementation. The particular source of the titanium is not known, although the suggestion is made that it is an alteration product of leucoxene.[5]

Source of Sediments. The close similarity in mineral content of every sample analyzed strongly suggests a single source for the heavy minerals of the Chester sandstone formations. Analyses of a few grab samples of the Mansfield sandstone, of Pennsylvanian age, overlying the Chester, reveal a heavy mineral suite almost identical with the average Chester mineral suite.

The mineralogical and physical character of the sands points toward an original source in an igneous rock with no particular evidence suggesting an intermediate period of deposition. The abundance of titaniferous material in the heavy mineral assemblage indicates a source in basic igneous rocks. The abundance of quartz, acid feldspar, zircon, and tourmaline suggest an acidic igneous source rock. Some of the more resistant minerals, such as tourmaline and zircon, and much of the quartz and feldspar may have been derived, in part, from pre-existing sediments.

The sands of the Chester formations are not considered to have been derived from the Pre-Cambrian crystallines to the north as these Pre-Cambrian rocks do not contain much titaniferous material; and studies of the heavy minerals in sediments closely adjacent to Pre-Cambrian rocks and thought to have been derived therefrom, do not reveal the presence of abundant leucoxene and titanium oxide minerals. Many of the Cambrian sands of Wisconsin have been examined but the presence of leucoxene has not been reported,[6,7] and the most characteristic heavy mineral is garnet. Ockerman reports garnet to make up 75 to 90 percent of the total heavy minerals in the Madison-Jordan formation. Pentland also reports abundant garnet in the Franconia-Mazomanie formation. The Chester sandstones are remarkably free of garnet.

Previous studies by R. C. Wallace and the writer[8] of Canadian sands considered to be derived from the Pre-Cambrian crystallines do not reveal leucoxene as a constituent.

[5] Leith, C. K. and Mead, W. J. Metamorphic Geology, p. 107.

[6] Ockerman, J. W., A Petrographic Study of the Madison and Jordan Sandstones of Southern Wisconsin, Jour. Geol., XXXVIII, 346 (1930).

[7] Pentland, A. G., The Heavy Minerals of the Franconia and Mazomanie Formations of Wisconsin, Unpublished Thesis, University of Wisconsin (1930).

[8] Wallace, R. C. and McCartney, G. C., Heavy Minerals in Sand Horizons in Manitoba and Eastern Saskatchewan, Trans. Royal Soc. of Canada, 3 ser., XXII, Sec. 4 (1928).

If the titaniferous rocks of Minnesota have supplied material to the Chester they should also have contributed to the Cambrian sands of Wisconsin. The absence of titaniferous material in the Cambrian plus the abundance of garnet as against the abundance of titaniferous material in the Chester plus the absence of garnet is strong evidence against a source of origin for the Chester sediments to the Northwest.

In the Adirondack region and southern Quebec there occur large bodies of anorthosite rock which contain considerable masses of titaniferous iron ore. The old crystalline rocks of the Adirondacks are made up of a succession of crystalline limestones, banded hornblende and biotite gneisses, pyritic and garnetiferous schists, amphibolites and quartzites.[9,10]

One of the important rock types of the Adirondack region is a garnetiferous schist. It hardly seems possible that if the Adirondack regions have supplied the titaniferous sediments of the Chester series that the garnet grains should not also have been incorporated. Garnet is recognized as a very resistant mineral, but in spite of this fact the mineral is practically absent in the Chester.

The Piedmont region of the eastern coast of United States is described as made up of "a complex of highly metamorphosed sedimentary and igneous materials."[11]

The Baltimore gneiss is an important unit in the northern part of the crystalline piedmont. It is described as a medium-grained thoroughly crystalline aggregate of quartz, feldspar, hornblende, and biotite. The Fordham gneiss is composed of quartz, feldspar, and biotite with accessory zircon, less apatite and titanite, and very infrequent magnetite.[12] The Carolina gneiss of Georgia is a formation made up of immense series of interbedded mica gneiss, garnet-kyanite gneiss, mica schist, quartz schist, garnet schist, etc.[13]

Closely allied with the gneisses described is the Wissahickon mica gneiss, which is a medium to coarse grained, banded rock

[9] Newland, D. H., Magnetites in the Adirondack Region, Econ. Geol., II, 763.
[10] Kemp, J. F., Geology of the Magnetites near Port Henry, Assn. Inst. Min. Eng., XXVII, 146–203 (1898).
[11] Bascom, F. (and others), Description of the Philadelphia district. U. S. Geol. Survey Geol. Atlas, Philadelphia folio (No. 162), 23 pp., maps (1909).
[12] Merrill, F. Description of the New York City District (N. Y.–N. J.) U. S. Geol. Survey, Geol. Atlas, New York City folio (No. 83), 19 pp., maps (1902).
[13] La Forge, L. and Phalen, W. P., Description of the Ellijay Quadrangle, U. S. Geol. Survey, Geol. Atlas Ellijay folio (No. 187), 18 pp., maps (1913).

characterized by an excess of mica. The chief constituents of the formation are quartz, feldspar, orthoclase and plagioclase, biotite and muscovite, magnetite, apatite, zircon, tourmaline, garnets, andalusite, sillimanite, and zoisite. The formation is very garnetiferous, especially near periodotite intrusives, and for this reason it is spoken of as garnetiferous mica schist.

There is the same difficulty in ascribing a source for the Chester sediments to the Piedmont rocks as that in the Adirondack rocks. If the Piedmont rocks supplied the sediments, the Chester formations should at least in part reflect such a history by the presence of the mineral garnet and possibly some of the other minerals characteristic of the metamorphosed Piedmont rocks, e.g., kyanite, andalusite, sillimanite, etc. These minerals are all comparatively resistant, but are not a part of the Chester sandstones.

It is realized, however, that this evidence in itself does not prove that the sediments could not have been derived from the Piedmont or the Adirondacks. Much of the erosion of rock terranes and transportation of sediments is done by rivers. It may well be the situation that the rigors of stream transportation have destroyed many of the minerals, and further, since rivers are known to be excellent sorting agents, many of the minerals which are known to be present in the rock terranes may have been removed during transportation by such sorting action.

An origin for the Chester sands in the crystalline Pre-Cambrian rocks of the St. Francis Mountain region does not seem possible since the mountains are thought to have been covered with Paleozoic sediments in Mississippian time.

There remains another possible source of origin for the Chester formation: the crystalline land mass known as Llanoria which at one time existed in the Gulf Coast region. There remains the question, however, of whether the crystalline rocks of Llanoria were capable of having supplied the highly titaniferous sediments of the Chester. This must remain an unanswered question until such time as the petrography of the crystallines and sediments known to have been derived therefrom is thoroughly studied. Bearing on this source is the fact that Brown has found a considerable quantity of leucoxene in sediments of Permian age in south central Oklahoma.[14]

[14] Brown, L. S., The Occurrence of leucoxene in some of the Permian Mid-Continent sediments, Am. Mineral., XIII, 233–235 (1928).

A STUDY OF THE HEAVY MINERALS OF THE PRE-CAMBRIAN AND PALEOZOIC ROCKS OF THE BARABOO RANGE, WISCONSIN

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ABSTRACT

The heavy minerals of the Huronian quartzite of the Baraboo Range consist mostly of zircon and rutile. There are occasional grains of biotite and apatite and rare grains of amphibole, augite, and magnetite. Secondary minerals are hematite and chlorite. No tourmaline was found in the quartzite, and only a single grain of garnet was seen. The heavy minerals in the quartzites are not different from those in the underlying igneous rocks.

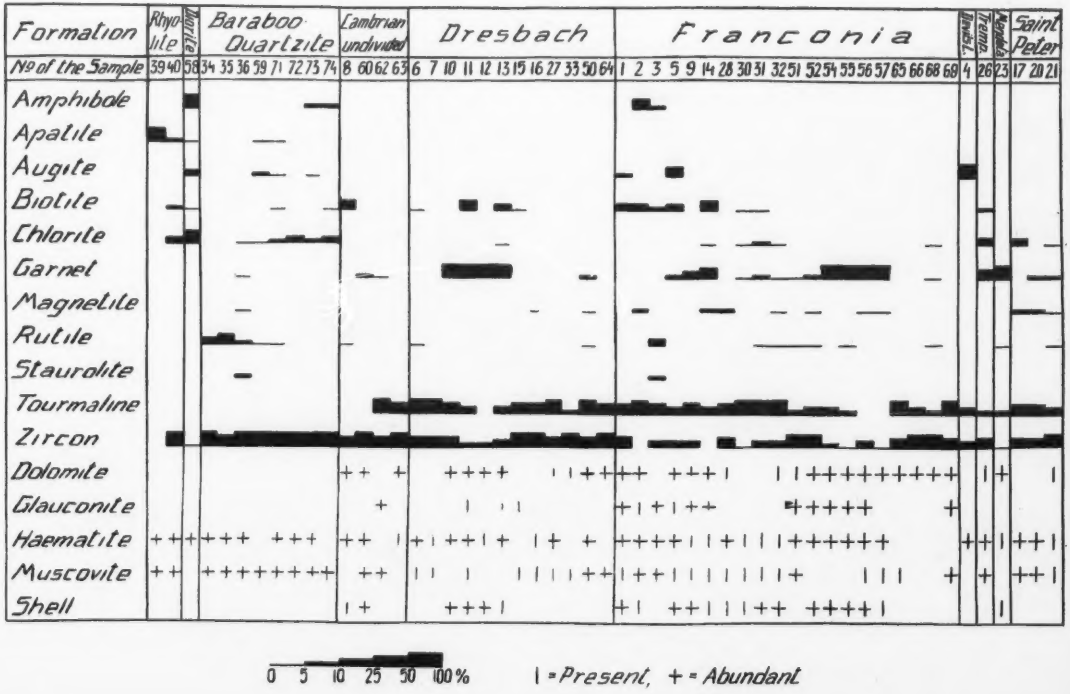
Zircon and tourmaline are common heavy minerals in the Paleozoic rocks. These rocks contain an abundance of garnet outside the Range, but this mineral is rare within the Range.

The extreme rareness of garnet and the apparent absence of tourmaline in the Huronian quartzite show that the materials for the Paleozoic sandstones were largely derived from sources other than the rocks of the Range and the rareness of garnet in the sandstones within the Range indicates that only limited quantities of sands were introduced from the outside.

STATEMENT OF THE PROBLEM

The Baraboo Range, composed of pre-Cambrian quartzite, slate, dolomite, iron formation, and some older underlying igneous rocks forms most of the hilly country around Baraboo. The pre-Cambrian rocks, which are folded in a large syncline, are surrounded and overlain by flat-lying Cambrian and Ordovician sandstones and limestones, all of which may grade into conglomerate on approach to the rocks of the syncline. It has generally been assumed that the quartzites and associated igneous rocks made important contributions to the Paleozoic sandstones and it was thought that some light might be thrown on this problem by a study of the minerals of the rocks involved.

The writer is indebted to Dr. W. H. Twenhofel for suggesting the problem and for help in its laboratory study. He also wants to thank other members of the teaching staff at the University of Wisconsin, especially Drs. A. Pentland, G. C. McCartney, R. R. Shrock, and Mr. G. O. Raasch for help and suggestion.


Formation
Rhyolite
Diorite
Baraboo Quartzite
Cambrian undivided
Dresbach
Franconia
Trempealeau
Saint Peter
No of the Sample
39 40 58 34 35 36 59 71 72 73 74 8 60 62 63 6 7 10 11 12 13 15 16 27 33 50 64 1 2 3 5 9 14 28 30 31 32 51 52 54 55 56 57 65 66 68 69 4 26 23 17 20 21
Amphibole
Apatite
Augite
Biotite
Chlorite
Garnet
Magnetite
Rutile
Staurolite
Tourmaline
Zircon
Dolomite
Glauconite
Haematite
Muscovite
Shell
0 5 10 25 50 100 %
| = Present, + = Abundant

THE MINERALS OF THE HURONIAN IGNEOUS ROCKS

The oldest rocks of the Baraboo district are rhyolite, diorite, and granite. Samples of rhyolite and diorite were crushed and their heavy minerals studied by means of heavy liquids.

The rhyolite contains much sericite and hematite. Zircon, mostly yellow but in some cases white, and more or less rounded, is common. Biotite, chlorite, and apatite also are present. No garnet or tourmaline was found.

The diorite contains large quantities of amphibole and chlorite, some augite (presumably enstatite), and small quantities of biotite, apatite, and zircon.

No specimen of the granite was available, as this rock is restricted to one small place. Weidman mentions it as containing a small quantity of mica, hornblende, and apatite.

THE MINERALS OF THE HURONIAN BARABOO QUARTZITE

The quantity of heavy minerals in the Baraboo quartzite ranges widely, from a few grains to several hundreds in 10 grams of rock, but the total quantity is less than 1 percent.

Except for hematite and muscovite, zircon is the most common heavy mineral. It occurs as well rounded grains of which the colors are yellow or white as in the rhyolite. Chlorite and rutile are present in most samples, more occasionally occur biotite, apatite, and rarely amphibole, augite, and magnetite. All these minerals are found in the older igneous rocks.

In one sample some particles of staurolite and one small particle of garnet were found. Tourmaline was not found in any sample. The quartzite also contains some feldspar.

THE MINERALS OF THE PALEOZOIC SANDSTONES

The samples studied were derived from the Dresbach and Franconia sandstones and Mendota dolomite of the upper Cambrian, and the Saint Peter sandstone of the Ordovician.

Zircon and tourmaline are common heavy minerals in all of these sandstones, and both minerals are common within and outside of the Range. Both occur in well rounded particles. The zircon is white, yellow, or pinkish and the tourmaline brown, gray, blue, and in some cases nearly black. Garnet is abundant outside the Range and always appears in angular pieces with conchoidal frac-

ture. The studies of Pentland[1] have shown that the Franconia-Mazomanie sandstones contain an abundance of garnet. This criterion holds well outside of the Range, but inside the Range garnet is missing or scarce in these sandstones, the ratio being 100 to 300 grains in a 10-gram sample from outside the Range, and 5 to 10 grains in a 10-gram sample from inside the Range.

So far as known, amphibole and augite are limited in their distribution to the surroundings of Devils Lake. This local occurrence of these easily destroyed minerals is probably referable to a local source.

Muscovite, biotite, and chlorite are common; less common are rutile, magnetite, and staurolite.

Some of the samples contain heavy minerals, not derived from older rocks. There are iron oxide, a carbonate (presumably mostly dolomite), and glauconite.

The light minerals contain some feldspar, mostly plagioclase. The quartz and other particles are rather generally well rounded except in the smaller dimensions; secondary enlargement is locally common. Much time was spent in trying to find quartz grains produced from fragments of the Baraboo quartzite. Some pinkish quartz grains were observed but no quartz grains were found which could be proven to have been derived from the quartzite.

SUMMARY

The following summary must be considered as tentative.

1. The heavy minerals in the Baraboo quartzite are mostly the same as in the igneous rocks that lie unconformably below the quartzite. But as similar igneous rocks are known in other parts of Wisconsin, this statement does not prove that the igneous rocks of the Baraboo Range were the source for the minerals of the overlying quartzites. Similar rocks farther away may have furnished the materials.

2. The presence of five grains of staurolite in the Baraboo quartzite indicates little, as the quantity is too small to mean anything. Zircon is common both in the quartzites, sandstones, and the igneous rocks beneath the quartzite.

3. The presence of tourmaline is common in the Cambrian

[1] Pentland, A., The heavy minerals of the Franconia and Mazomanie sandstones, Jour. Sed. Pet., 1, 23–36 (1931).

sandstones, whereas it is entirely lacking in the pre-Cambrian. It seems that its source must be outside of the Range.

4. Garnet, except for a single grain, is one sample that has not been found in the pre-Cambrian. It is rare or wanting in Cambrian sandstones within the Range and is common outside the Range. The rareness inside the Range indicates that the quartzite was an important contributor to the sandstones inside the Range but that there were some contributions from outside. The abundance of garnet in the sandstones outside the Range indicates that large contributions came from sources other than the Range. The amphibole and augite in the Cambrian sandstones seems to be confined to the surroundings of Devils Lake and points to a local source. The fair rounding of the quartz and heavy minerals indicates long transportation.

THE OCCURRENCE OF MOISSANITE (SILICON CARBIDE) IN SEDIMENTS

ROBERT D. OHRENSCHALL[1] AND CHARLES MILTON[2]

Silicon carbide was first described by Moissan[3] in 1893, and shortly afterwards was produced in this country on a large scale by Acheson under the name of Carborundum. In 1905, Moissan[4] reported silicon carbide present in the Canyon Diablo meteorite. In honor of the discoverer, the substance occurring naturally has been termed Moissanite.

It has generally been assumed that moissanite is restricted to meteorites, no other instance of its occurrence having been reported. In this paper numerous occurrences will be cited, leading to the conclusion that the mineral has a widespread, though sparing, distribution. It has been found in various parts of the world, in formations ranging in age from Ordovician to Recent.

The following table summarizes the occurrences observed by the writers to date:

TABLE 1
GEOLOGIC OCCURRENCE OF MOISSANITE

Country	Age	Formation
United States		
Tennessee	Pleistocene	Loess, outcrop
Tennessee	Mississippian	Phosphate nodule, outcrop
Indiana	Mississippian	Limestone, building stone
New York	Palaeozoic	Limestone, building stone
Venezuela	Miocene	Sandstone, outcrop
Angola	Cretaceous	Marl, cable-tool well cuttings
Panama	Miocene	Sandstone cable-tool well cuttings

Larsen[5] has briefly summarized the optical and other properties of moissanite. Moissan, in describing the silicon carbide of the Canyon Diablo meteorite, states fully all the physical properties of

[1] Rhodesia Minerals Concession, Ltd.
[2] The Johns Hopkins University.
[3] Moissan, Henri, Preparation et proprietes du siliciure de carbone cristallisé, Compt. Rendu., CXVII, 425–428 (1893).
[4] Moissan, Henri, Étude du siliciure de Carbone de la Météorite de Canon Diablo, Compt. Rendu., CXL, 45–46 (1905).
[5] Larsen, E. S., The Microscopic Determination of the Non-opaque Minerals, U. S. Geol. Survey, Bull. 679, pp. 112, 192 (1921).

the mineral. In this occurrence, he describes the fragments as being of all colors, especially emerald green. The grains examined by the writers were found to range from nearly colorless to deep sapphire blue, and only in one case, emerald green. The green grain is from the Panama occurrence.

The colored grains are markedly pleochroic, the directions of maximum absorption agreeing with that given for carborundum. Basal sections yield good uniaxial positive interference figures.

The very high refractive index, fresh conchoidal fracture and bluish color are perhaps the most diagnostic features. Many grains have an almost metallic luster due to the high index which is greater even than diamond. None of the fragments show any effect whatever of abrasion, the characteristic conchoidal fracture being perfectly sharp. Some of the grains are so deeply colored as to appear nearly opaque.

Although apparently widespread, moissanite occurs somewhat sparingly. Where found in the heavy concentrate (using bromoform) of an average sized sample, generally only one or two grains are present. In size they are about a tenth of a millimeter in diameter. In two cases, however, a rather abundant yield was obtained from the samples examined. A phosphatic nodule from the Maury green shale of Tennessee weighing about 25 grams yielded about 20 particles of moissanite, together with some rutile, zircon, magnetite, and ilmenite. The Panama well sample also furnished numerous grains.

That the silicon carbide found in these samples is contamination of carborundum is a natural supposition, yet several considerations make this unlikely. Some of the outcrop samples were collected personally by the writers, and in these cases, at least, they are confident that contamination could not have occurred. Nor does it seem that carborundum could have been introduced during the laboratory treatment of the samples.

Furthermore, our experience with this substance has been closely duplicated by that of Mrs. Fanny Edson, subsurface geologist for the Roxana Petroleum Corporation, at Tulsa, Oklahoma. She states[6] that she has been finding sapphire blue grains in her slides of heavy mineral concentrates for the past six years. Dr. C. S. Ross of the United States Geological Survey has identified

[6] Personal communication.

them as being identical with carborundum.[7] Regarding the question of contamination Mrs. Edson states:

1. I never have used, nor use, carborundum in my laboratory, so there is no possible way the carborundum could have been introduced into the samples in my laboratory preparation.

2. I rarely find more than one or two grains in a slide and then only in about one out of twenty slides. If it is carborundum introduced from the outside and not a component mineral of the sample, why is it not more common and abundant?

3. Extensive inquiry has failed to reveal that carborundum is used in drilling wells, and there appears to be no source for carborundum at the well. If it were introduced into the sample why again is it not more common and abundant?

4. I find the mineral in outcrop samples as frequently and abundantly as in well samples; there would be no way for outcrop samples to become contaminated except in the laboratory, and as mentioned under (1) there is no carborundum in the laboratory.

5. Our samples, both outcrop and from wells, are always put in clean cloth sample sacks. No source of contamination there.

Mrs. Edson also states that she finds this mineral in formations ranging in age from Ordovician to Permian.

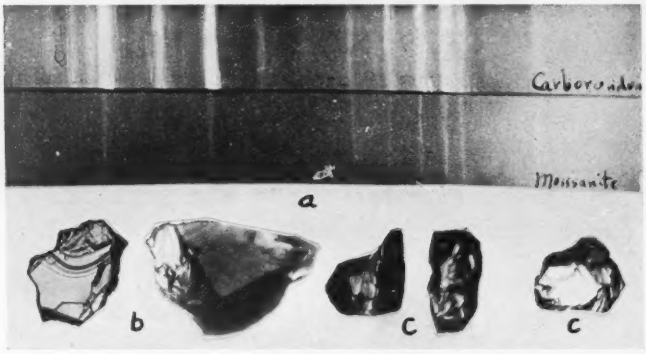


Figure 1. (a) X-ray diagram of Moissanite (below) and of known Carborundum (above). (b) Moissanite grains from phosphate nodule collected at outcrop, Tennessee (×50). (c) Moissanite grains from sandstone well cuttings, Darien, Panama (×50).

For corroborative evidence that the mineral is silicon carbide, an x-ray spectrogram of several grains was kindly made by the General Electric Company, of Schenectady. The material for this

[7] Personal communication.

determination was isolated from the heavy mineral concentrates of the sandstone sample from Panama and the nodule from Tennessee. The grains were powdered, and commercial carborundum was used as the calibration substance. The correspondence of the spectral lines is quite satisfactory in view of the minute amount of material available.

From the foregoing, it seems that the substance is silicon carbide of natural origin. The question arises as to its source.

Silicon carbide has not been reported as a constituent of any igneous or metamorphic rock. Often, it is true, an occasional fragment is found in thin-sections, but this is due to carelessness in preparing the section, when carborundum is used as an abrasive. In view of Moissan's discovery of silicon carbide in the Canyon Diablo meteorite, and considering the great amount of material of extra-terrestrial origin which is continually reaching the surface of the earth, it is plausible that the occurrences listed above may arise from the disintegration of cosmic fragments either in the atmosphere, or in the earth's crust subsequent to burial of meteoric material. Silicon carbide is virtually indestructible chemically or mechanically, and would remain unchanged indefinitely when the nickel-iron, silicates, and other meteoric substances had completely disappeared.

The writers wish to express their appreciation to Dr. Thomas A. Wilson of the General Electric Company, for the x-ray analysis, and to Dr. J. C. Hubbard, Dr. Emil Ott, and to Dr. A. H. Pfund, all of the Johns Hopkins University, for assistance in connection with the x-ray spectrogram.

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NEW PUBLICATIONS

FREDERICK G. TICKELL, *The Examination of Fragmental Rocks: Stanford University Press*, 1931, 127 pages, 51 figures, Price $5.00.

In his varied duties as professor of petroleum engineering and investigator of subsurface oilfield problems, Professor Tickell has enjoyed exceptional opportunites of becoming familiar with many methods of examining rock fragments. After ten years or more of experimenting with these methods, and after the completion of several important pieces of research by means of them, he has at last seen fit to describe and illustrate those that appear to him most useful. Some idea of the scope of his work may be gained from the following summary.

After a brief introductory chapter, the author discusses the problem of determining and stating the size of grains in a heterogeneous aggregate. He includes visual methods, screening, and elutriation, discusses the determination of degree of rounding, the making and use of different types of frequency curves, and the use of polished surfaces and thin sections in studying the texture of a solid aggregate of minerals such as a sedimentary rock. The last section makes no reference to the use of bakelite as a cement. The chapter was prepared too early to include references to interesting papers by Rubey[1] and Trask[2] who have recently made important contributions to the art of making and recording mechanical analyses of fine-grained rocks. As it stands, however, it is an interesting and valuable summary of all the more important methods of mechanical analysis, except a few of those most recently devised.

The third chapter, on porosity and permeability, contains likewise a workmanlike discussion, with many references to papers by Meinzer, Melcher, Russell, Sutton, Nutting, and other students. There is a beautiful illustration of a mercury volumeter, along with directions for using it in making rapid determinations of porosity.

In Chapter IV the author discusses the preparation and clean-

[1] Rubey, W. W., Lithologic Studies of Fine-grained Upper Cretaceous Sedimentary Rocks of the Black Hills Region, U. S. Geol. Survey, Prof. Paper 165-A, pp. 14–31 (1930).

[2] Trask, Parker D., Mechanical Analyses of Sediments by Centrifuge, Econ. Geology, pp. 581–599 (1930).

ing of specimens for microscopic study, and describes the more important methods that have been used in separating the constituents of the clean material into classes. Panning, heavy mineral separation, magnetic, electrostatic, and dielectric separation are all discussed and references are given to the more important earlier discussions, many of them published in non-geological journals. The chapter is concluded by an account of the author's method of making permanent mounts of sand grains or other fragments of comparable size.

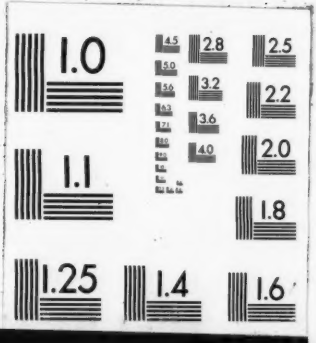
The identification of minerals is treated in a long chapter intended to be practical rather than theoretical, and to require no previous knowledge of optical mineralogy. The chapter is certainly interesting to read, and contains many valuable suggestions. How efficiently and correctly it would enable a previously untrained microscopist to identify mineral grains, the reviewer hesitates to guess. If the aspirant could practice under competent direction while reading it, as many students probably have done in Professor Tickell's laboratory, the result might be very satisfactory. This chapter contains an interesting discussion of orientation-cleavage diagrams, with illustrations of their usefulness. The diagrams for the amphiboles have inadvertently been drawn with the obtuse angle between the prism faces (110) in the wrong place. Inasmuch as the diagrams are presumably meant primarily to be suggestive to a student who may wish to make similar drawings for his own use, the error is hardly of importance. Aside from the ordinary optical methods discussed, this chapter contains also a valuable section on spectographic examination, and an illustration of the arc spectra of several minerals.

Chapter VI lists the optical properties of more than 50 of the more important detrital minerals, and includes some ingenious tables that should be of much assistance in their indentification under the microscope.

This book is clearly written, well illustrated, and substantially and attractively bound. Aside from the features already mentioned, it contains many excellent illustrations, some of them from original photographs, and a bibliography of more than 100 titles. In this day of intensive study of rock samples collected from wells, it should attain a wide circulation among laboratory workers and others interested in the subject it discusses.

R. D. REED

Los Angeles, California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